HIGH-RESOLUTION SATELLITE IMAGERY: A REVIEW OF METRIC ASPECTS

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ABSTRACT

With the era of commercial high-resolution earth observation satellites having dawned with the launch in September, 1999 of *Ikonos-2*, it is imperative that there is an understanding in the photogrammetric and remote sensing communities of the full metric potential of high-resolution satellite line scanner imagery. This paper discusses the metric exploitation of 1m satellite imagery, and specifically looks at the options available for multi-image restitution in situations where optimal ground point triangulation accuracy is sought. Such applications would include automated DTM generation and high-accuracy feature determination for both mapping and geopositioning. The paper commences with a brief discussion of accuracy aspects and then overviews the collinearity model for orientation/triangulation of line scanner imagery. Alternative restitution models are then reviewed. These include rational functions, the direct linear transformation and an affine projection approach. Each restitution model has its merits and limitations, and of central importance is the provision or lack of provision of the 'camera models' for the different high-resolution satellite systems. With the prevailing level of uncertainty over just what critical sensor calibration information will be made available by the satellite imaging companies, there is consequently a need for a range of alternative, practical approaches for extracting accurate 3D terrain information from 1m satellite imagery.

1 INTRODUCTION

In September 1999, with the successful launch of the *Ikonos-2* satellite by Space Imaging, the photogrammetry and remote sensing communities entered the era of commercial high-resolution earth observation satellites. One of the great promises of *Ikonos*, and its planned competitors such as *Quickbird* and *Orbview III* (e.g. Fritz, 1995) is that 1m satellite imagery will display the metric quality to support topographic mapping to large scales, and even to scales of larger than 1:10,000, as well as ground feature determination from multispectral imagery to better than 5m accuracy. In order to meet the necessary metric accuracy specifications, appropriate mathematical models and computational procedures will be required. Although there has been more than a decade of experience gained with exterior orientation (EO) determination and subsequent ground point triangulation of line scanner imagery, metric exploitation of 1m satellite imagery will bring with it some new challenges. These are unlikely to relate to accuracy requirements alone. Instead, much will depend upon the provision or lack of provision of the necessary sensor calibration model and precise satellite ephemeris data to support optimal multi-image restitution.

In the past 15 years or so there has been a good deal of research attention paid to the recovery of 3D cartographic information from satellite line scanner imagery. Initial impetus was provided by the formulation of mathematical models to support both batch and on-line triangulation of cross-track *SPOT* imagery (e.g. Westin, 1990; Kratky, 1989). This was followed by developments in 3-line image restitution for systems such as the German *MOMS-02* satellite sensor (Ebner et al., 1992) and refinement of sensor orientation models for the Indian *IRS-1C/D* satellite line scanners (Radhadevi et al., 1998). In broadly summarising the result of these endeavours, it could be said that under ideal conditions of high-quality image mensuration and ground control/checkpoints, coupled with favourable imaging geometry (e.g. base-to-height ratio of 0.8 or more) and provision of sensor calibration data, ground point determination to 0.3 pixels is possible (Ebner et al., 1996), whereas accuracies of between 0.5 and 2 pixels are more commonly encountered in practical tests. Thus, for *SPOT* stereo scenes, accuracies at the 5-10m range in planimetry and 10-20m range in height are readily achievable. The corresponding figures for 5m resolution imaging systems such as *MOMS-02* and *IRS-1C/D* are close to 5m in planimetry and 4-20m in height. The accuracy range in heighting is primarily a function of the various base-to-height ratios encountered in cross-track stereo scenes.

Notwithstanding the presence of imaging perturbations, such as atmospheric refraction, that can be expected to influence steerable 1m satellite sensors to a greater degree than *SPOT* or *IRS*, extension of the experience gained with 10m- and 5m-resolution sensors would suggest that ground point determination to an accuracy of a metre or so should be readily attainable with 1m imagery, especially in multi-image configurations. Irrespective of whether the final accuracy capability of *Ikonos* and other 1m-resolution satellites is 0.5 pixels or 3 pixels, the impact on topographic mapping and map revision can be expected to be significant. Indeed, a 2 pixel ground point accuracy would enable *Ikonos* imagery to be employed for cartographic product generation to a scale of as large as 1:10,000, which covers most topographic mapping. Given the potential for 1m satellite imagery to render aerial photography at scales of smaller than 1:20,000 obsolescent, it is useful to consider the available options for 3D metric exploitation of 1m satellite imagery.

Within the photogrammetric and remote sensing industries there is a wide desire to metrically exploit 1m satellite imagery to the maximum extent possible. This implies application of a fully rigorous mathematical model for orientation and triangulation, which in turn implies provision of sensor calibration data and, to a degree, prior information on the satellite orbit and sensor attitude data. Where this critical data is not available, there is no alternative but to resort to less comprehensive restitution models which might be expected to yield lower metric accuracy. As matters stand at this writing (February, 2000), users of 1m stereo *Ikonos* imagery will be denied access to the 'camera model' which could hinder optimal metric exploitation of the imagery. The withholding of essential sensor calibration data is seen by the satellite imagery providers as necessary for the retention of a competitive edge in the provision of value-add services in the high end of the metric product market.

Thus, alternative restitution models will need to be called upon to allow orientation and triangulation of *Ikonos* stereo imagery. In this paper a number of these alternative models are reviewed, and their applicability to 1m imagery is predicted based on experience gained with lower resolution push-broom satellite imaging systems. Initially, however, some further comments are offered on the accuracy prospects for 1m satellite imagery.

2 ACCURACY POTENTIAL

Whereas the specifications for *Ikonos* image products state that a 1-sigma ground point precision of as high as 0.9m will be attainable, some simulation studies published to date (e.g. Li and Zhou, 1999) point to more modest expectations of 2-3m for planimetric and vertical accuracy, the principal factor limiting precision being the accuracy to which the sensor EO can be determined in flight by the on-board GPS receivers and star trackers. In the absence of ground control, but with the inclusion of measured ephemeris data, the triangulation accuracy falls off to around 12m (Li and Zhou, 1999), though it should be kept in mind that this is representative more of uncertainty in absolute position as opposed to a measure of relative accuracy within the restitution of the *Ikonos* scene. One could anticipate that the '90% Circular Error' of 50m in planimetry for the *Ikonos Geo* product could well be considerably improved via simple two-dimensional transformation involving a modest number of ground control points.

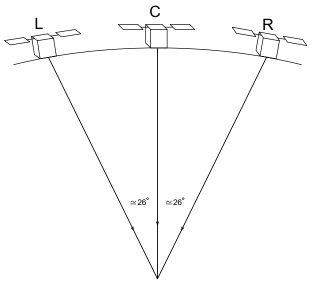

Figure 1: Imaging Geometry.

Consider, for example, the imaging configuration for *Ikonos* illustrated in Figure 1. Under the assumption of an image measurement accuracy of 0.5 pixel (σ_{xy} = 5μm), the ground point triangulation precision to be anticipated for the geometry indicated by sensor positions L and R, which have a base-to-height ratio of b/h = 1, is σ_{XY} = 0.32m (planimetry) and σ_Z = 0.67m (height). If this stereo geometry is extended to three along-track images, L, C and R, the triangulation precision in Z remains unchanged (see also Ebner et al, 1992), whereas the planimetric precision is improved to σ_{XY} = 0.25m, or ¼ of the ground sample distance. In order to recover this level of accuracy, however, an optimal orientation model must be utilised.

As it happens, it is unlikely that a standard EO of the 2-image (L and R) network could be achieved via a central perspective model such as a modified collinearity approach (Sect.3) without the imposition of constraints on the EO parameters, notably positional constraints based on precise ephemeris data. This is due to instability that results from over-parameterization. It is well known that for the standard six EO parameters, the pitch angle is very highly correlated to position along the flight line, and the roll angle displays strong projective coupling to cross-strip position. For the 2-image configuration represented by L and R in Figure 1, correlation coefficients exceeding 0.99 can be anticipated with a bundle adjustment that does not employ EO constraints. To some degree the addition of the central image removes this instability and allows for a bundle adjustment to be carried out in the absence of EO constraints. Nevertheless, attention must still be paid to solution stability.

3 FUNDAMENTAL MATHEMATICAL MODEL

3.1 Modified Collinearity Equations

Prior to the discussion of alternative sensor orientation models for satellite imagery, a brief review is provided of what is acknowledged to be the most rigorous restitution model for satellite image orientation and triangulation. The well-known collinearity equations, which provide the fundamental mathematical model for restitution of photogrammetric frame imagery, are equally applicable to satellite line scanner imagery, though in modified form. The modified model takes into account the fact that the line scanner represents a perspective projection in the cross-track direction (y) only, and a parallel projection in the x, or flight-line direction. This yields the following equations related to a particular scan line at time t:

$$\begin{aligned} 0 - x_0 &= - c\, X^1 / Z^1 \\ y_t - y_0 &= - c\, Y^1 / Z^1 \end{aligned} \qquad (1)$$

and

$$(X^1,Y^1,Z^1)^T = \mathbf{R}_t\,[(X-X^c_t), (Y-Y^c_t), (Z-Z^c_t)]^T$$

where y_t is the image coordinate within the scan line (the x coordinate is zero); x_0, y_0 are the coordinates of the principal point; c is the principal distance; X, Y, Z are the coordinates of the ground point; X^c_t, Y^c_t, Z^c_t are the object space coordinates of the sensor at time t; and $\mathbf{R}_t$ is the sensor orientation matrix, again at time t.

In order to perform EO and subsequent ground point triangulation using Eqs. 1, it is necessary to model the orientation parameters ($\mathbf{R}_t$, X^c_t, Y^c_t, Z^c_t) as a function of time, otherwise the model is too over-parametrerised to support practical implementation. The modelling of the sensor platform dynamics as a function of time or scan-line number is less problematic for spaceborne sensors than for airborne linear array scanners due to the relatively smooth and quite well described orbital trajectory of the satellite.

3.2 Bundle Adjustment Formulation

In the case where the orbital parameters of the satellite are known *a priori*, the positional elements of the EO can be constrained to some degree. This incorporation of prior knowledge regarding satellite motion can range from the simple assumption that the EO parameters vary either linearly or as a quadratic function over a short arc length, to the case where $\mathbf{R}_t$ and X^c_t, Y^c_t, Z^c_t are accurately known through the use of on-board GPS and star trackers which determine sensor attitude angles. A common approach, lying somewhere between these two, is to enforce the platform motion to be in accordance with a true Keplerian orbital trajectory. Thus, the 'shape' of the trajectory is assumed known *a priori,* but not the position. With these considerations in mind, a combined mathematical model for satellite line scanner imagery can be written as

$$\begin{aligned} \mathbf{v} &= \mathbf{A}_1\mathbf{x}_1 + \mathbf{A}_2\mathbf{x}_2 + \mathbf{A}_3\mathbf{x}_3 - \ell \qquad &&; \mathbf{P} \qquad (2) \\ \mathbf{v}_c &= \mathbf{C}_1\mathbf{x}_1 \qquad\qquad\; + \mathbf{C}_3\mathbf{x}_3 - \ell_c &&; \mathbf{P}_c \end{aligned}$$

where $\mathbf{x}_1$, $\mathbf{x}_2$ and $\mathbf{x}_3$ represent the EO, object point and additional parameters, respectively; $\mathbf{A}_1$, $\mathbf{A}_2$ and $\mathbf{A}_3$ are the related design matrices; $\mathbf{C}_1$ and C_3 are coefficient matrices of orbital constraint functions; $\mathbf{v}$ and $\mathbf{v}_c$ are vectors of residuals; ℓ and ℓ_c

are discrepancy vectors; and **P** and $\mathbf{P}_c$ are weight matrices, the former relating to image coordinate observation precision, the latter to the constraint function(s). Depending on the model adopted, the 'additional parameters', $\mathbf{x}_3$, might comprise 'drift' terms, 'calibration' parameters or orbital perturbation terms.

Eqs. 2 represent a form of the photogrammetric bundle adjustment, or least-squares multi-image orientation/ triangulation adjustment, which provides a 3D ground point determination for DTM extraction or feature positioning. Under the assumption that there are two or more overlapping images with appropriate imaging geometry, the success to be expecting in applying this modified bundle adjustment will be heavily dependent on a number of factors, for example the triangulation geometry, the number of ground control and pass points, the precision of the image coordinate observations and the degree to which the orbital parameters of the satellite and attitude of the sensor (i.e. X_t^c, Y_t^c, Z_t^c and $\mathbf{R}_t$) are known *a priori.*

Up until the time of launch of the *Ikonos* 1m satellite in September 1999, all earth observation satellites familiar to the remote sensing community lacked the provision of precise orbital information, thus precluding the straightforward implementation of tight platform orientation and position constraints via Eqs. 2. Instead, alternative constraint formulations were employed. These included a dynamic modelling of the German *MOMS-2P* 3-line imaging system (deployed on the Mir Space station), whereby orbital constraints (position only) were applied (Ebner et al., 1996); and adoption of the concept of multiple projection centres or 'orientation images', again for the triangulation of *MOMS* imagery, by Ebner et al. (1992) and Fraser & Shao (1996). Prior to the launch of *MOMS-02*, which undertook two missions in the early and mid 1990s, similar triangulation models had been formulated and applied for *SPOT* imagery (e.g. Westin, 1990) and *IRS-1C* (Radhadevi et al., 1998).

Given the provision of GPS and star trackers on both the *Ikonos* satellite and the two future 1m satellites, *Earlybird* and *Orbview III*, there have been expectations in the photogrammetric and remote sensing communities of the possibility of implementing Eqs. 2 to the fullest metric extent, since the EO of each scan line will be known to about 2-3m in position and 2-3 arc seconds in attitude. This suggests, even before rigorous analysis, that point positioning accuracies of 2-3m in planimetry and height will be achievable, given a strong intersection geometry (e.g. base-to-height ratio of 0.8 to 1) and image mensuration to a precision of 1 pixel or better.

It is therefore understandable why 1m satellite imagery is seen to hold such great potential for topographic mapping and the revision of topographic databases. As mentioned, however, it is not clear whether the precise ephemeris data for 1m satellites will be made available to the remote sensing community. Hence, there is the prospect that alternative constraint functions to straightforward position and attitude data will still be required in the application of Eqs. 2 for ground point triangulation. Moreover, the level of triangulation precision referred to above may therefore not be achievable. The strong dependence of the bundle adjustment formulation of Eqs. 2 on sufficiently precise preliminary EO values suggests that alternative formulations to the collinearity equation model need to be examined.

3.3 Image Mensuration Precision

Any discussion of the accuracy potential of multi-image restitution is incomplete without reference to the precision of image coordinate mensuration. After all, triangulation accuracies achieved ulilising automated tie point connection and refined area-based image matching to 0.1 pixel precision can be expected to be three times better than those achieved with feature-based matching to 0.3 pixel, and an order of magnitude superior to results obtained with image coordinate observations to 1 pixel accuracy. Nevertheless, in the following discussion this aspect is not touched upon when the results of applying different triangulation models are discussed. As it happens, image mensuration accuracies of between 0.3 and 0.5 pixels were obtained in the practical experiments mentioned in the following discussion, and such observational precision can be anticipated in controlled practical applications. It can only be presumed that the same will be true for 1m satellite imagery.

4 ALTERNATIVE MODELS

4.1 Multiple Projection Centre Model

In the absence of the continuous sensor attitude data and sensor orbital parameters, a re-parameterisation of the collinearity equations, Eqs. 1 is required. Individual EO elements (X_t^c, Y_t^c, Z_t^c and the attitude angles forming $\mathbf{R}_t$) are replaced by time dependent polynomial functions. Essentially, the image is subdivided into a number of sections. At the centre scan line of each section there are six unknown EO elements, which are often referred to as 'orientation images'. In the intervals between these reference scan lines, first-order, quadratic or higher-order polynomial functions are used to describe the smooth variation in sensor EO.

This approach has been successfully employed in the triangulation of *MOMS-02* 3-line imagery (Kornus et al., 1995; Fraser & Shao, 1996), where Lagrange polynomials were used to model sensor position and attitude over the scan line interval between adjacent reference lines, the third-order variation function for an EO parameter being given as

$$P_3(t) = \sum_{i=OI-1}^{OI+2} P(t_i) \prod_{\substack{j=OI-1 \\ j \neq i}}^{OI+2} \frac{t - t_j}{t_i - t_j} \qquad (3)$$

where $P_3(t)$ at time t is a linear combination of $P(t_i)$ at the four adjacent orientation images. A perceived advantage of the Lagrange polynomial approach is that the interpolation function is dependent only upon the nearest one or two orientation images on each side of a given scan line. Generally speaking, the shorter the interval between reference lines, the lower the order of the interpolation function. There is often a balancing act required: too many reference lines lead to a less well conditioned solution, which may necessitate additional ground control and pass points. On the other hand, fewer orientation images implies that the adopted interpolation function can adequately model the dynamically changing EO of the sensor.

Application of the multiple projection centre model, or interpolative platform model, does not require a priori knowledge of the satellite orbit, though provision of approximate EO parameters does aid in solution convergence. In applying this approach to *MOMS* imagery, Fraser and Shao (1996) used reference line intervals varying from 4000 to 8000, and ground control arrays comprising from 4 to 20 points. Accuracies attained in ground point triangulation were in the order of 0.5 to 1 pixel, though it was noted that the method is prone to a measure of numerical instability, and is thus very sensitive to observational errors.

While extrapolation of these orientation results for lower resolution satellites to the case of 1m imagery may be by no means a robust indicator, results obtained with the *MOMS-02* and *IRS-1C* sensors suggest that triangulation accuracies approaching the 1-pixel level might well be achievable. Thus, absence of the provision of prior EO information may not constitute a significant impediment to attaining high accuracy results with 1m imagery. One important factor which cannot be overlooked, however, is that application of the collinearity equation model with multiple projection centres still requires a comprehensive knowledge of sensor interior orientation, though it is possible to self-calibrate the sensor provided the necessary (and not terribly practical) imaging geometry is in place (e.g. Ebner et al., 1992).

4.2 Rational Functions

As a practical means of extracting 3D information from stereo satellite imagery in the absence of either a camera model or EO data, a model based on 'rational functions' has been proposed. Rational functions are polynomial-based, empirical models which generally comprise terms to third order and express image coordinates as a direct function of object space coordinates, in much the same way as do collinearity equations. These functions, which provide a continuous mapping between image and object space, are given as a ratio of polynomials comprising coefficients that defy straightforward geometric interpretation. Indeed, it is said that one reason rational functions gained popularity for military imaging satellites was that the satellite orbital elements and also the EO could not be derived from the rational function coefficients.

A general model for the rational function approach, which is appropriate for mono and stereo imaging configurations, is given as

$$\begin{aligned} x_t &= \frac{a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ + a_7XYZ + a_8X^2 + \ldots + a_{19}Z^3}{1 + b_1X + b_2Y + b_3Z + b_4XY + b_5XZ + b_6YZ + b_7XYZ + b_8X^2 + \ldots + b_{19}Z^3} \\ y_t &= \frac{c_0 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ + c_6YZ + c_7XYZ + c_8X^2 + \ldots + c_{19}Z^3}{1 + d_1X + d_2Y + d_3Z + d_4XY + d_5XZ + d_6YZ + d_7XYZ + d_8X^2 + \ldots + d_{19}Z^3} \end{aligned} \qquad (4)$$

where x_t, y_t are the image coordinates and X,Y,Z the object point coordinates. As can be seen from Eqs. 4, a number of existing restitution algorithms for line scanner imagery are based on special formulations of the ratio-of-polynomials model (e.g. the DLT and polynomial expressions in which the denominator is reduced to unity).

Rational functions have previously found application in photogrammetry as a restitution model for the real-time loop in analytical stereoplotters, and they have well established advantages and disadvantages. Among the principal advantages are sensor independence (a combination of different sensors is possible) and speed. They are fast enough for real-time implementation, can accommodate any object space coordinate system, and can be tuned (e.g. selection of a subset of parameters) for particular sensors. Among the disadvantages are the possible need to tune the functions for particular sensors, the subjectivity associated with parameter selection (there can be 80 parameters for a stereo pair), and the fact that they are prone to numerical instability and require more object space control.

Hence, although developers of digital photogrammetric workstations can provide necessary restitution software based on rational functions, application of this model can require careful attention. For the experienced practitioner, the costs of polynomial-based restitution approaches are well known in terms of the need for extra ground control and tie points in a multi-image scene. These inconveniences may be avoided, however, if the rational functions are obtained along with the imagery from the satellite image provider, and not derived by the customer. The metric impact of this empirical modelling approach is yet to be fully quantified for 1m satellite imagery, though it is unlikely that the majority of end users will be too concerned about questions of minor accuracy differences. The remote sensing and photogrammetric communities have, after all, long been achieving accuracies with polynomial models for satellite line scanner imagery that can reach the one pixel level in favourable situations. Nevertheless optimal 3D feature extraction accuracy is, by design, unlikely to be achieved via vendor-supplied rational function coefficients.

It is not inconceivable that shortly after high-resolution satellite imagery becomes available, photogrammetic research groups will achieve a self-calibration of the imaging sensors and publish their own camera models. In the meantime, however, all parties in the mapping industry, the image providers, the photogrammetric system developers and companies performing stereo-based value adding, will potentially be able to proceed with product generation by utilising vendor supplied rational function coefficients.

4.3 A Direct Linear Transformation Approach

Restitution models based on linear projective equations have already proved practical in close-range photogrammetry, in spite of some well-known shortcomings in comparison to the collinearity equation model. The most widely used of these models is the Direct Linear Transformation (DLT), a variation of which has been proposed by Wang (1999) for triangulation of satellite line scanner imagery. As was alluded to earlier, the DLT also represents a special case of the rational function model, with the form proposed by Wang (1999) being as follows:

$$
\begin{aligned}
x_t &= \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \\
y_t &= \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} + L_{12}\, x_t\, y_t
\end{aligned}
\qquad (5)
$$

This model is effectively the 'standard' DLT for frame imagery supplemented with an extra image coordinate correction parameter, L_{12}. Multi-image triangulation based on Eqs. 5 does not require knowledge of sensor interior orientation, and nor does it require preliminary estimates of sensor EO.

Implicit in the formulation of Eqs. 5 is the assumption that the dynamic behaviour of the sensor trajectory and attitude can be adequately modelled with variation functions of first-order. This would imply that the DLT approach is most suited to scenes of limited geographical extent. Experiments reported by Wang (1999) indicated that, for *SPOT* imagery covering a 60 x 60 km area, the DLT approach yielded the same level of triangulation accuracy as the more rigorous collinearity equation model with multiple projection centres (Eq. 3). Moreover, the model yielded 1 pixel triangulation accuracy in the restitution of a stereo *IRS-1C* scene covering an area of approximately 25 x 25 km. This was achieved without the usual requirements associated with the collinearity equation approach utilising polynomials to model EO, namely the need for sensor calibration and satellite ephemeris data, and the requirement that careful attention be given to controlling parameter correlations and therefore parameter weighting.

4.4 An Affine Projection Model

The final satellite triangulation approach to be discussed is a model based on affine as opposed to perspective projection. Under this approach, which is described in Okamoto et al. (1999) and Hattori et al. (2000), an initial transformation of the image from a perspective to an affine projection is first performed. A linear transformation from image to object space then follows, which depending on the particular affine model formulation adopted, may involve the modeling of coefficients as linear functions of time. Formulation of the affine model was motivated by a recognition that as the field of view of the linear array scanner becomes small, high correlations develop between EO parameters within a perspective projection since the narrow bundle of rays effectively approaches a parallel projection. It should be recalled that the field angle of the *Ikonos* sensor is less than 1°.

The model for 3D analysis of line scanner imagery via a 2D affine model is given in the form (Okamoto et al., 1999)

$$\begin{aligned} x_a &= D_1X + D_2Y + D_3 Z \\ y_a &= D_4X + D_5Y + D_6 Z \end{aligned} \qquad (6)$$

As mentioned, application of Eqs. 6 first requires an image conversion from central perspective (x_t,y_t) to affine projection (x_a,y_a), which although needing a prior knowledge of terrain height, approximate sensor position and look angle, is nevertheless reasonably insensitive to coarse initial estimates of both due to the iterative nature of the conversion (Okamoto et al., 1998).

Practical implementation of the affine projection model has been performed using both stereo *SPOT* images and *MOMS-2P* imagery (forward- and backward-looking channels only). In one experiment, in the Kobe/Osaka test field in Japan, ground point triangulation accuracies to sub-pixel level, namely 6-8m, were obtained in planimetry and height (Okamoto at el., 1999; Hattori et al. 2000) for a SPOT stereo pair under conditions of modest ground control point (<10 points). A further test with a MOMS-2P stereo image pair over Bavaria also yielded ground point triangulation accuracies of better than 1 pixel (18m), the RMS value at 50 checkpoints being 10-12m in planimetry and height. Given certain conditions, the 'bundle adjustment' formulated using Eqs. 6 does not need to incorporate a linear variation function for the sensor EO parameters. In performing the bundle adjustment, attention to appropriate parameter weighting to enhance solution stability is usually warranted, though in the Kobe/Osaka test field, which covered 60 x 40 km and incorporated 130 check points, stable solutions were routinely obtained with as few as four control points.

In spite of some theoretical shortcomings in the perspective to affine image conversion, and in spite of the modelling of coefficients D_i in Eqs. 6 as time-invariant, the affine model has provided triangulation accuracies equivalent to and in some cases better than the central perspective model with multiple projection centres. Moreover, the method is equally applicable to along-track and cross-track stereo imaging configurations, and given the narrow view angle of high-resolution imaging satellites such as *Ikonos*, the affine approach may well be quite suited to the orientation of 1m resolution imagery.

5. CONCLUDING REMARKS

The aim of this paper has been effectively two-fold, firstly to highlight the metric potential of the new series of 1m resolution Earth observation satellites for cartographic product generation, and secondly to illustrate that moderately high ground point triangulation accuracies can be anticipated with 1m imagery through use of non-rigorous, though practical multi-image restitution models. The adoption of such models, rather than the rigorous collinearity equations with sensor orbital and attitude constraints, will become a necessity in situations where the camera model and precise ephemeris data are withheld from the user community.

At this writing (February, 2000) we are only a month or so into full commercial sales of *Ikonos* imagery, and it is therefore not surprising that there is little experimental indication as yet of the true metric potential of 1m satellite imagery.

Nevertheless, in extrapolating from the experimental results reported here, there can be a high degree of confidence that ground point triangulation accuracies at the 1-2 pixel level will be readily achievable, and this triangulation precision may well be obtained with some or all of the alternative restitution models described in this paper.

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